First Single Molecule, C_{60} Nanotransistor Fabricated

"Bouncing Ball" Oscillations Observed, Coupling Electrical and Mechanical Motion

A research team led by Paul McEuen, Paul Alivisatos, and Erik Anderson has fabricated the first single-molecule transistors that are based on individual C_{60} molecules The team also discovered that these nanotransistors exhibit a unique coupling between mechanical motion and electronic properties as the C_{60} molecule "bounces" between the electrical contacts. A report of the work recently appeared in *Nature*.

The electronic properties of C_{60} and its carbon nanotube relatives have been of interest since the discovery of this materials system in the early 1990's. LBNL has been at the forefront in synthesizing materials in this family (Highlight 98-8) and in predicting their electronic properties (Highlight 96-7). One of the most formidable challenges in the study of these new nanomaterials, however, is developing methods to study them on their characteristic length scale, that is, at the molecular level. In response to this need, LBNL has developed a series of new techniques for fabricating nanosized devices and has used them to demonstrate a number of new and interesting electronic phenomena (Highlights 98-3, 00-8, 00-9).

In this work, the team adapted a technique they had developed to study "ropes" of carbon nanotubes (Highlight 00-8). Electron beam lithography performed by MSD's "Nanowriter" was used to define a grid of narrow gold wires on a silicon wafer. The wires were 200 nm wide and 10 nm thick. The ends of these wires were attached to lithographically defined bond pads to allow electrical contact. A high current was then run through the wires, inducing "electromigration," the movement of atoms in a metal subject to a large current density. In this case, this caused the wires to narrow and finally break in a controllable and self-limiting fashion, opening a 1 nm wide gap. A dilute solution of C_{60} molecules was dispersed on the wafer, and the solvent was evaporated. In a significant number of cases, a single C_{60} molecule settled into the gap between the contacts. The insulating SiO_2 layer on the Si substrate served as a gate electrode, thus completing the three contacts required to form a transistor (see figure).

Transistor function was evaluated by measuring the source-drain current as a function of gate and source-drain voltage (see figure). Two interesting effects were observed. The presence of triangular regions indicates that for a given gate voltage (x-axis), there are periodic ranges of source-drain voltages for which no current flows. This shows that, unlike an ordinary transistor, the C_{60} transistor has a "conductance gap." This effect, which the team had observed previously in other "quantum dot" devices, is due to the finite energy required to add (remove) a single electron to (from) the C_{60}. Second, the presence of narrowly spaced parallel lines in the 2-D data revealed the presence of conductance "steps" where the current changed rapidly with small changes in the either the source-drain or gate voltage. By examining several working transistors, it was found that the steps were spaced about 5 milli-electron volts (meV) apart. The investigators determined that the steps occur when a new tunneling pathway is opened for electrons to "hop" onto the C_{60}; therefore, the steps probe excited states of the C_{60} molecule. The characteristics of this excitation were consistent with the coupling of a C_{60} vibration to the electron motion, but its energy was more than 5 times smaller than the lowest energy C_{60} vibration. However, the group showed that a simple one-dimensional center of mass analysis predicted that the "bouncing" of the C_{60} molecule in the 1 nm gap between the contacts in a given transistor in response to the gain or loss of an electron would have the requisite characteristic vibrational quantum of ~5 meV. They therefore concluded that, although the device functions as a transistor, the motion of the C_{60} molecule between the contacts modulates its electronic properties. This is the first time that such a coupling between mechanical motion and electron motion has been observed on the nanoscale.

This discovery of coupling of electronic and mechanical degrees of freedom is likely to be important in electronic transport in a wide variety of nano-molecular systems. Here, the single C_{60} molecule behaves as a high frequency (1.2 THz) nano-mechanical oscillator when current is flowing through the device. This demonstrates that the motion of single molecules can be probed (or excited) directly by single electron events, and one can image nanoelectronic applications involving either the use of single electrons to actuate the motion of the C_{60} or, alternatively, the use of external forces to move the C_{60} and thus influence the motion of single electrons. Interestingly, this work demonstrates the need to treat the motion of components in nanoelectronics in a quantized fashion; they can be true quantum-"mechanical" systems.

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H. Park, J. Park, A. K. L. Lim, E. H. Anderson, A. P. Alivisatos, and P. L. McEuen, "Nano-mechanical oscillations in a single-C_{60} transistor, *Nature* (2000).